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Lu et al.

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(54) **MODEL-PLANT MISMATCH DETECTION USING MODEL PARAMETER DATA CLUSTERING FOR PAPER MACHINES OR OTHER SYSTEMS**

(58) **Field of Classification Search**
CPC .. G05B 13/041; G05B 13/04; G05B 23/0254; G05B 17/02; G05B 2219/25298
(Continued)

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(73) Assignee: **Honeywell Limited**, Mississauga (CA)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 313 days.

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(65) **Prior Publication Data**

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(57) **ABSTRACT**

A method includes repeatedly identifying one or more values for one or more model parameters of at least one model associated with a process. The one or more values for the one or more model parameters are identified using data associated with the process. The method also includes clustering the values of the one or more model parameters into one or more clusters. The method further includes identifying one or more additional values for the one or more model parameters using additional data associated with the process. In addition, the method includes detecting a mismatch between the at least one model and the process in response to determining that at least some of the one or more additional values fall outside of the one or more clusters. The values could be clustered using a support vector machine.

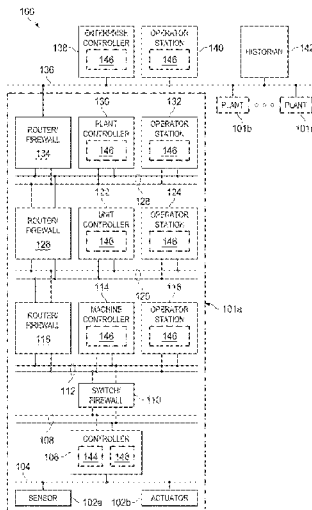
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(52) **U.S. Cl.**
CPC **G05B 13/041** (2013.01); **G05B 13/04** (2013.01); **G05B 17/02** (2013.01); **G05B 23/0254** (2013.01); **G05B 2219/25298** (2013.01)

17 Claims, 6 Drawing Sheets



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 USPC 700/30
 See application file for complete search history.

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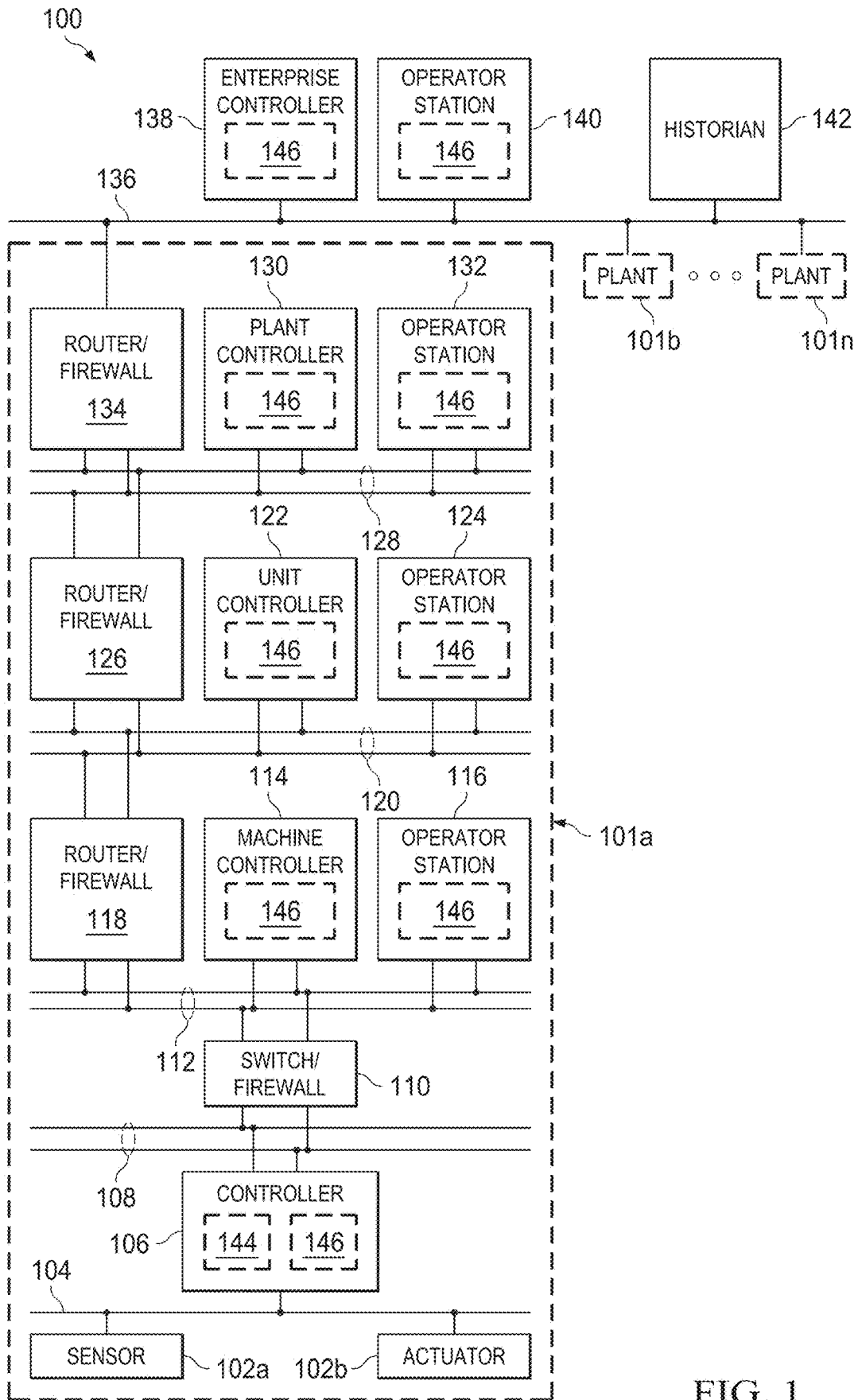


FIG. 1

FIG. 2

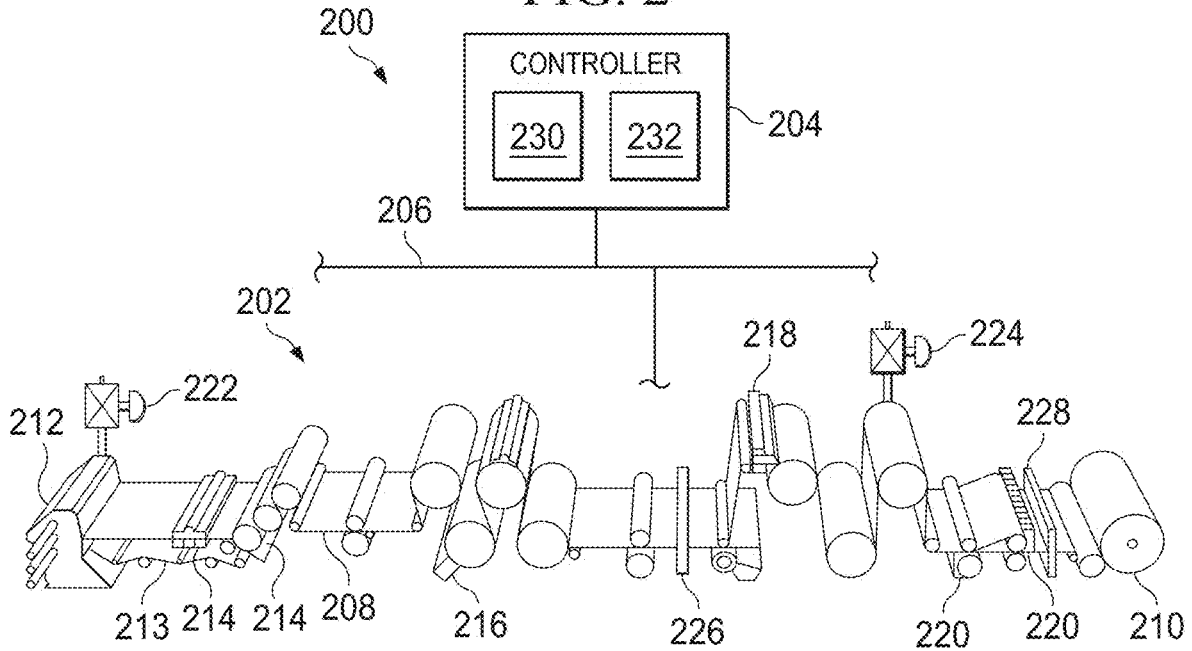
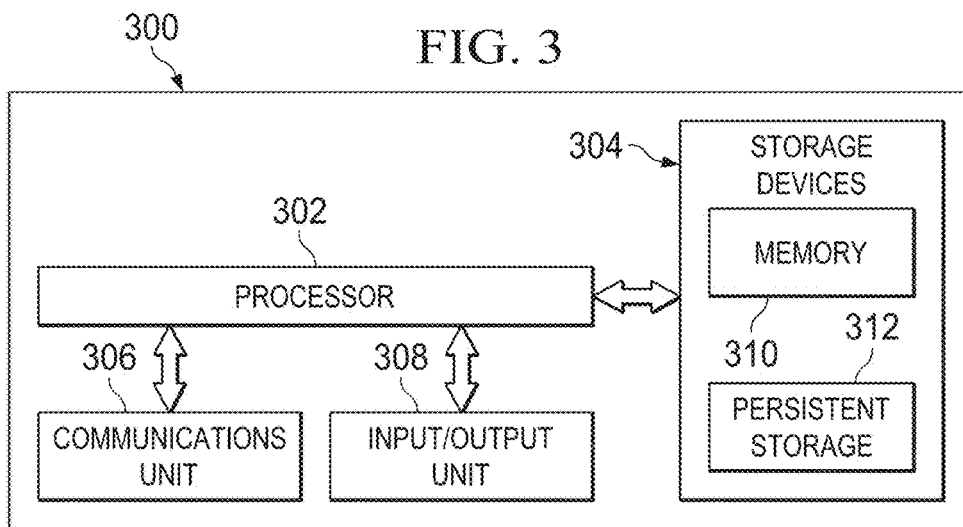


FIG. 3



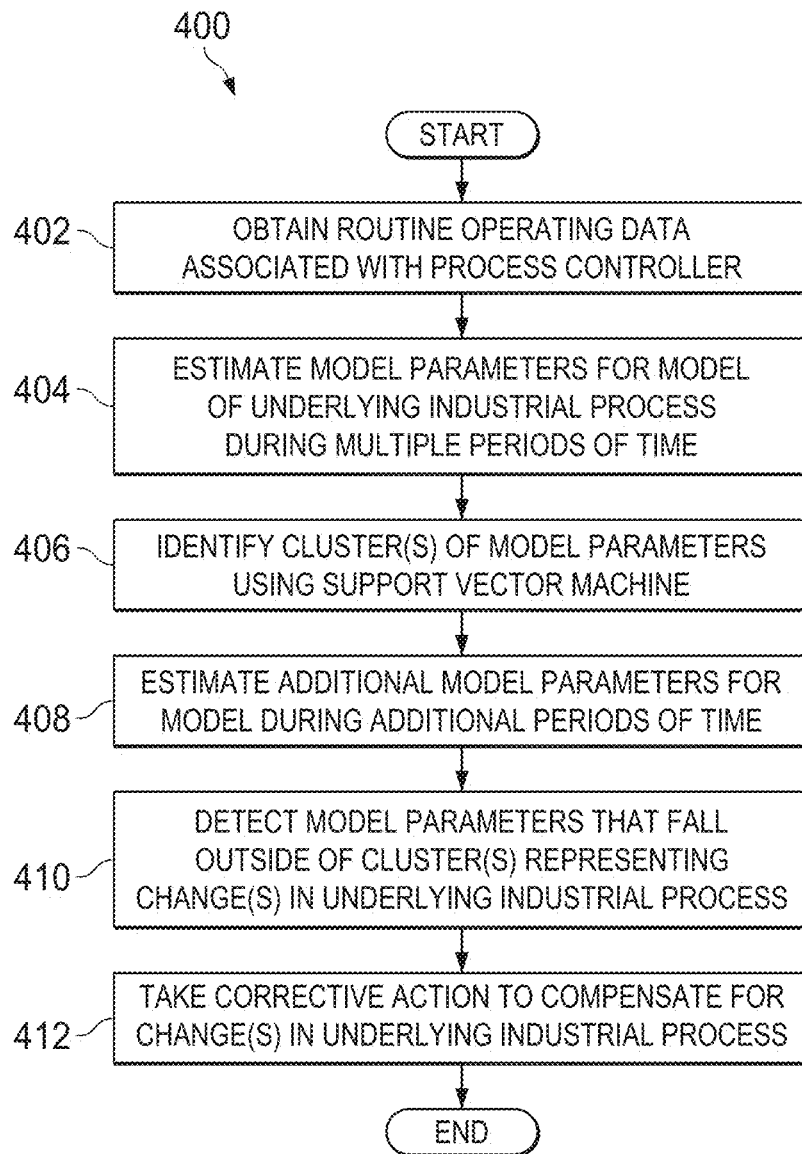


FIG. 4

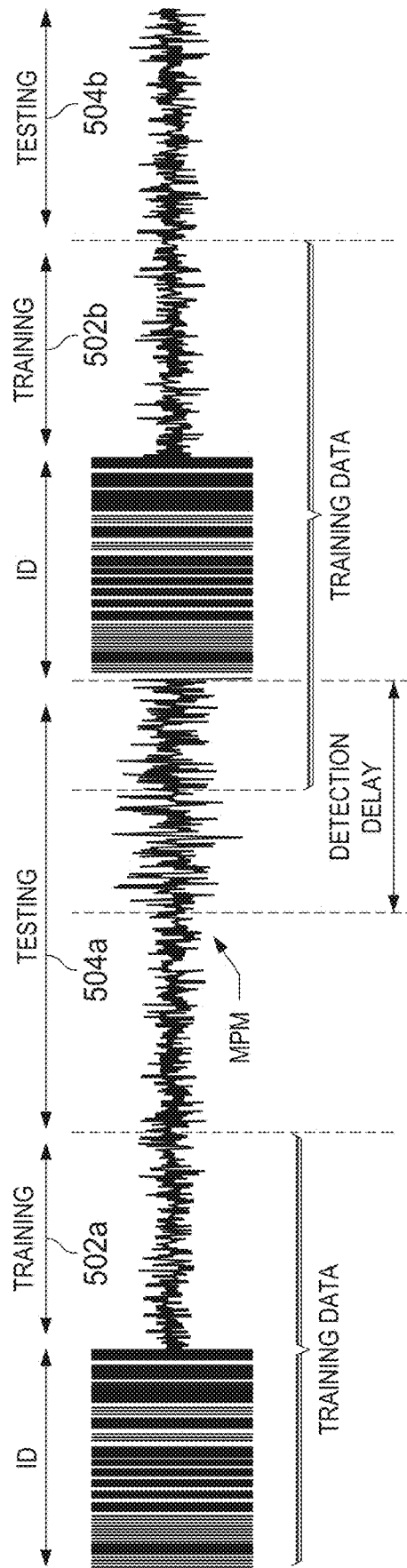


FIG. 5

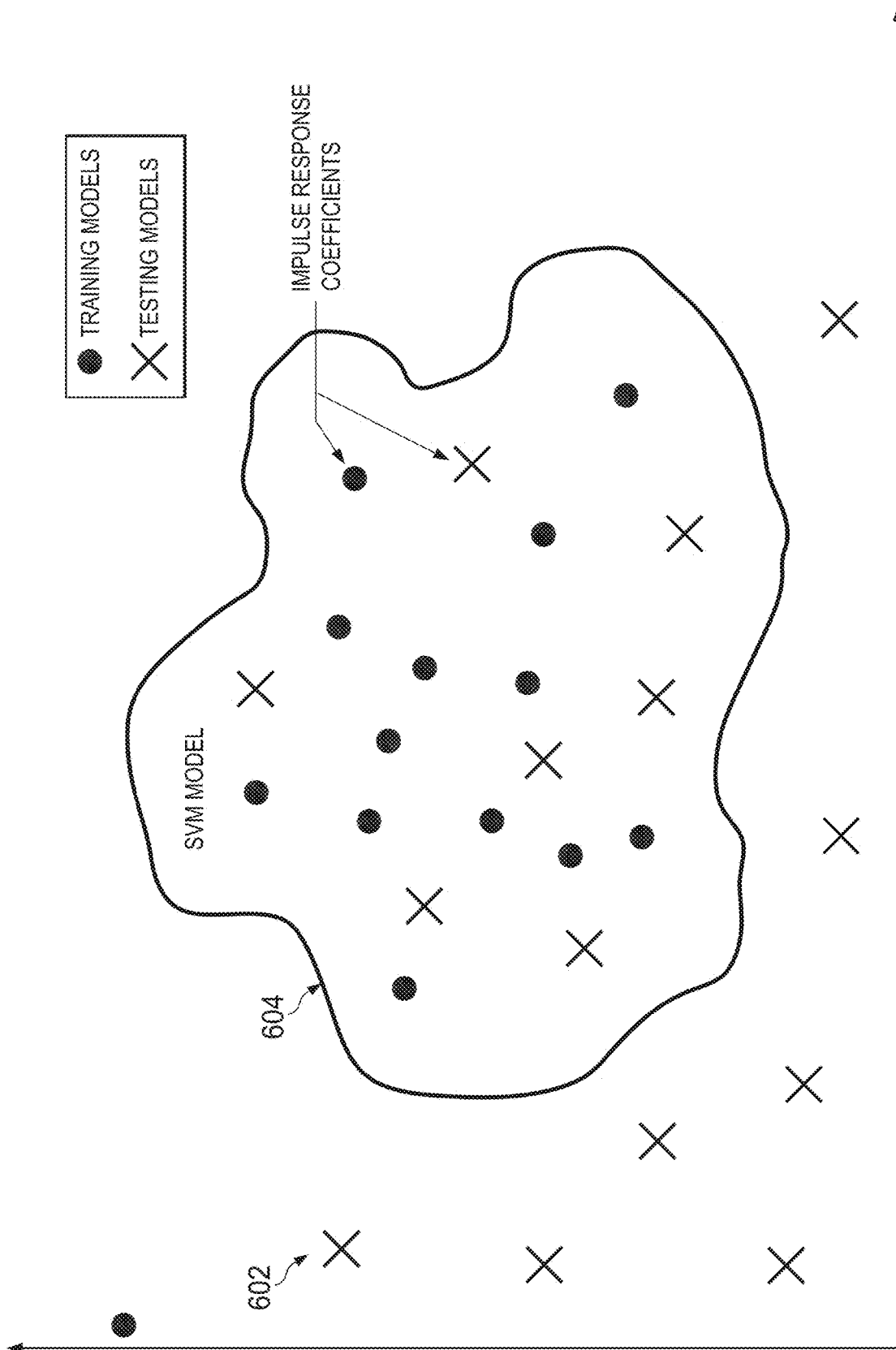


FIG. 6

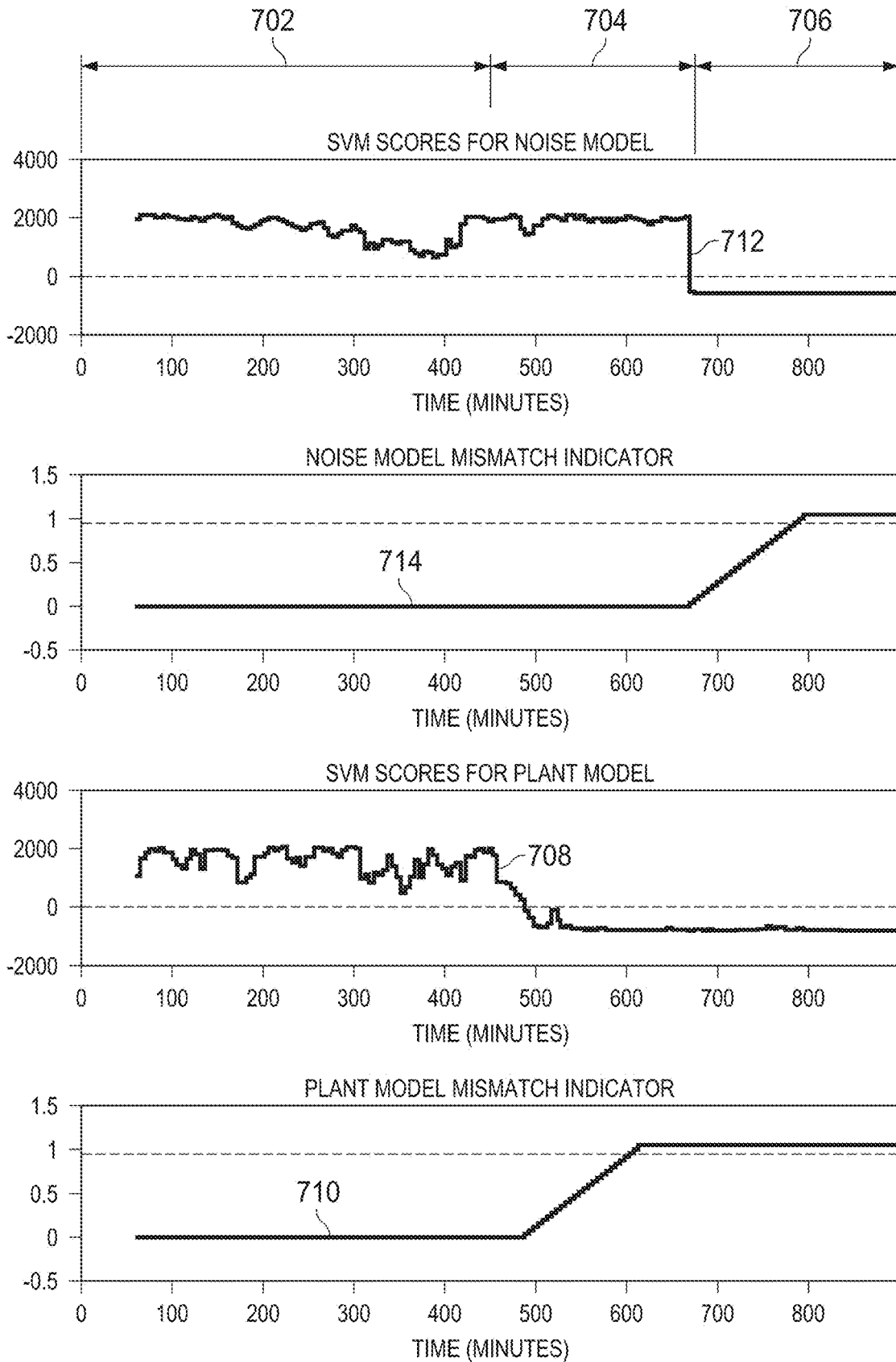


FIG. 7

**MODEL-PLANT MISMATCH DETECTION
USING MODEL PARAMETER DATA
CLUSTERING FOR PAPER MACHINES OR
OTHER SYSTEMS**

CROSS-REFERENCE TO RELATED
APPLICATION AND PRIORITY CLAIM

This application claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Patent Application No. 62/395,950 filed on Sep. 16, 2016, which is hereby incorporated by reference in its entirety.

TECHNICAL FIELD

This disclosure relates generally to industrial process control and automation systems. More specifically, this disclosure relates to model-plant mismatch detection using model parameter data clustering for paper machines or other systems.

BACKGROUND

Industrial process control and automation systems are often used to automate large and complex industrial processes. These types of control and automation systems routinely include process controllers and field devices like sensors and actuators. Some of the process controllers typically receive measurements from the sensors and generate control signals for the actuators. Model-based industrial process controllers are one type of process controller routinely used to control the operations of industrial processes. Model-based process controllers typically use one or more models to mathematically represent how one or more properties within an industrial process respond to changes made to the industrial process.

SUMMARY

This disclosure provides model-plant mismatch detection using model parameter data clustering for paper machines or other systems.

In a first embodiment, a method includes repeatedly identifying one or more values for one or more model parameters of at least one model associated with a process. The one or more values for the one or more model parameters are identified using data associated with the process. The method also includes clustering the values of the one or more model parameters into one or more clusters. The method further includes identifying one or more additional values for the one or more model parameters using additional data associated with the process. In addition, the method includes detecting a mismatch between the at least one model and the process in response to determining that at least some of the one or more additional values fall outside of the one or more clusters.

In a second embodiment, an apparatus includes at least one memory configured to store data associated with a process. The apparatus also includes at least one processing device configured to repeatedly identify one or more values for one or more model parameters of at least one model associated with the process using the data associated with the process. The at least one processing device is also configured to cluster the values of the one or more model parameters into one or more clusters. The at least one processing device is further configured to identify one or more additional values for the one or more model param-

eters using additional data associated with the process. In addition, the at least one processing device is configured to detect a mismatch between the at least one model and the process in response to determining that at least some of the one or more additional values fall outside of the one or more clusters.

In a third embodiment, a non-transitory computer readable medium contains instructions that, when executed by at least one processing device, cause the at least one processing device to repeatedly identify one or more values for one or more model parameters of at least one model associated with a process. The one or more values for the one or more model parameters are identified using data associated with the process. The medium also contains instructions that, when executed by the at least one processing device, cause the at least one processing device to cluster the values of the one or more model parameters into one or more clusters. The medium further contains instructions that, when executed by the at least one processing device, cause the at least one processing device to identify one or more additional values for the one or more model parameters using additional data associated with the process. In addition, the medium contains instructions that, when executed by the at least one processing device, cause the at least one processing device to detect a mismatch between the at least one model and the process in response to determining that at least some of the one or more additional values fall outside of the one or more clusters.

Other technical features may be readily apparent to one skilled in the art from the following figures, descriptions, and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of this disclosure, reference is now made to the following description, taken in conjunction with the accompanying drawings, in which:

FIG. 1 illustrates a first example industrial process control and automation system according to this disclosure;

FIG. 2 illustrates a second example industrial process control and automation system according to this disclosure;

FIG. 3 illustrates an example device supporting model-plant mismatch detection using model parameter data clustering according to this disclosure;

FIG. 4 illustrates an example method for model-plant mismatch detection using model parameter data clustering according to this disclosure; and

FIGS. 5 through 7 illustrate example uses of model-plant mismatch detection according to this disclosure.

DETAILED DESCRIPTION

FIGS. 1 through 7, discussed below, and the various embodiments used to describe the principles of the present invention in this patent document are by way of illustration only and should not be construed in any way to limit the scope of the invention. Those skilled in the art will understand that the principles of the invention may be implemented in any type of suitably arranged device or system.

As noted above, model-based industrial process controllers are one type of process controller routinely used to control the operations of industrial processes. Model-based process controllers typically use one or more models to mathematically represent how one or more properties within an industrial process respond to changes made to the industrial process. Model-based controllers typically require accurate models of process behaviors in order to perform

well. As conditions related to an industrial process change, the models for that process typically need to be updated. However, it is often difficult to determine from routine operating data whether a model accurately describes the true process behavior of an industrial process. Moreover, performing an experiment to improve the quality of the data for this purpose is often undesirable because the experiment may affect the quality of one or more products being manufactured or processed in the industrial process.

As described in more detail below, this disclosure provides techniques for detecting significant model-plant mismatch using routine operating data. When mismatch is detected, existing models can be updated or new models can be created and used to control an industrial process, helping to maintain the quality of products being manufactured or processed in the industrial process.

FIG. 1 illustrates an example industrial process control and automation system **100** according to this disclosure. As shown in FIG. 1, the system **100** includes various components that facilitate production or processing of at least one product or other material. For instance, the system **100** is used here to facilitate control over components in one or multiple plants **101a-101n**. Each plant **101a-101n** represents one or more processing facilities (or one or more portions thereof), such as one or more manufacturing facilities for producing at least one product or other material. In general, each plant **101a-101n** may implement one or more processes and can individually or collectively be referred to as a process system. A process system generally represents any system or portion thereof configured to process one or more products or other materials in some manner.

In FIG. 1, the system **100** is implemented using the Purdue model of process control. In the Purdue model, “Level 0” may include one or more sensors **102a** and one or more actuators **102b**. The sensors **102a** and actuators **102b** represent components in a process system that may perform any of a wide variety of functions. For example, the sensors **102a** could measure a wide variety of characteristics in the process system, such as temperature, pressure, or flow rate. Also, the actuators **102b** could alter a wide variety of characteristics in the process system. The sensors **102a** and actuators **102b** could represent any other or additional components in any suitable process system. Each of the sensors **102a** includes any suitable structure for measuring one or more characteristics in a process system. Each of the actuators **102b** includes any suitable structure for operating on or affecting one or more conditions in a process system.

One or more networks **104** are coupled to the sensors **102a** and actuators **102b**. The network **104** facilitates interaction with the sensors **102a** and actuators **102b**. For example, the network **104** could transport measurement data from the sensors **102a** and provide control signals to the actuators **102b**. The network **104** could represent any suitable network or combination of networks. As particular examples, the network **104** could represent an Ethernet network, an electrical signal network (such as a HART or FOUNDATION FIELDBUS network), a pneumatic control signal network, or any other or additional type(s) of network(s).

In the Purdue model, “Level 1” includes one or more controllers **106**, which are coupled to the network **104**. Among other things, each controller **106** may use the measurements from one or more sensors **102a** to control the operation of one or more actuators **102b**. Each controller **106** includes any suitable structure for controlling one or more

aspects of a process system. As a particular example, each controller **106** could represent a computing device running a real-time operating system.

Redundant networks **108** are coupled to the controllers **106**. The networks **108** facilitate interaction with the controllers **106**, such as by transporting data to and from the controllers **106**. The networks **108** could represent any suitable redundant networks. As particular examples, the networks **108** could represent a pair of Ethernet networks or a redundant pair of Ethernet networks, such as a FAULT TOLERANT ETHERNET (FTE) network from HONEYWELL INTERNATIONAL INC.

At least one switch/firewall **110** couples the networks **108** to two networks **112**. The switch/firewall **110** may transport traffic from one network to another. The switch/firewall **110** may also block traffic on one network from reaching another network. The switch/firewall **110** includes any suitable structure for providing communication between networks, such as a HONEYWELL CONTROL FIREWALL (CF9) device. The networks **112** could represent any suitable networks, such as a pair of Ethernet networks or an FTE network.

In the Purdue model, “Level 2” may include one or more machine-level controllers **114** coupled to the networks **112**. The machine-level controllers **114** perform various functions to support the operation and control of the controllers **106**, sensors **102a**, and actuators **102b**, which could be associated with a particular piece of industrial equipment (such as a boiler or other machine). For example, the machine-level controllers **114** could log information collected or generated by the controllers **106**, such as measurement data from the sensors **102a** or control signals for the actuators **102b**. The machine-level controllers **114** could also execute applications that control the operation of the controllers **106**, thereby controlling the operation of the actuators **102b**. In addition, the machine-level controllers **114** could provide secure access to the controllers **106**. Each of the machine-level controllers **114** includes any suitable structure for providing access to, control of, or operations related to a machine or other individual piece of equipment. Each of the machine-level controllers **114** could, for example, represent a server computing device running a MICROSOFT WINDOWS operating system. Although not shown, different machine-level controllers **114** could be used to control different pieces of equipment in a process system (where each piece of equipment is associated with one or more controllers **106**, sensors **102a**, and actuators **102b**).

One or more operator stations **116** are coupled to the networks **112**. The operator stations **116** represent computing or communication devices providing user access to the machine-level controllers **114**, which could then provide user access to the controllers **106** (and possibly the sensors **102a** and actuators **102b**). As particular examples, the operator stations **116** could allow users to review the operational history of the sensors **102a** and actuators **102b** using information collected by the controllers **106** and/or the machine-level controllers **114**. The operator stations **116** could also allow the users to adjust the operation of the sensors **102a**, actuators **102b**, controllers **106**, or machine-level controllers **114**. In addition, the operator stations **116** could receive and display warnings, alerts, or other messages or displays generated by the controllers **106** or the machine-level controllers **114**. Each of the operator stations **116** includes any suitable structure for supporting user access and control of one or more components in the system **100**. Each of the

operator stations **116** could, for example, represent a computing device running a MICROSOFT WINDOWS operating system.

At least one router/firewall **118** couples the networks **112** to two networks **120**. The router/firewall **118** includes any suitable structure for providing communication between networks, such as a secure router or combination router/firewall. The networks **120** could represent any suitable networks, such as a pair of Ethernet networks or an FTE network.

In the Purdue model, "Level 3" may include one or more unit-level controllers **122** coupled to the networks **120**. Each unit-level controller **122** is typically associated with a unit in a process system, which represents a collection of different machines operating together to implement at least part of a process. The unit-level controllers **122** perform various functions to support the operation and control of components in the lower levels. For example, the unit-level controllers **122** could log information collected or generated by the components in the lower levels, execute applications that control the components in the lower levels, and provide secure access to the components in the lower levels. Each of the unit-level controllers **122** includes any suitable structure for providing access to, control of, or operations related to one or more machines or other pieces of equipment in a process unit. Each of the unit-level controllers **122** could, for example, represent a server computing device running a MICROSOFT WINDOWS operating system. Although not shown, different unit-level controllers **122** could be used to control different units in a process system (where each unit is associated with one or more machine-level controllers **114**, controllers **106**, sensors **102a**, and actuators **102b**).

Access to the unit-level controllers **122** may be provided by one or more operator stations **124**. Each of the operator stations **124** includes any suitable structure for supporting user access and control of one or more components in the system **100**. Each of the operator stations **124** could, for example, represent a computing device running a MICROSOFT WINDOWS operating system.

At least one router/firewall **126** couples the networks **120** to two networks **128**. The router/firewall **126** includes any suitable structure for providing communication between networks, such as a secure router or combination router/firewall. The networks **128** could represent any suitable networks, such as a pair of Ethernet networks or an FTE network.

In the Purdue model, "Level 4" may include one or more plant-level controllers **130** coupled to the networks **128**. Each plant-level controller **130** is typically associated with one of the plants **101a-101n**, which may include one or more process units that implement the same, similar, or different processes. The plant-level controllers **130** perform various functions to support the operation and control of components in the lower levels. As particular examples, the plant-level controller **130** could execute one or more manufacturing execution system (MES) applications, scheduling applications, or other or additional plant or process control applications. Each of the plant-level controllers **130** includes any suitable structure for providing access to, control of, or operations related to one or more process units in a process plant. Each of the plant-level controllers **130** could, for example, represent a server computing device running a MICROSOFT WINDOWS operating system.

Access to the plant-level controllers **130** may be provided by one or more operator stations **132**. Each of the operator stations **132** includes any suitable structure for supporting user access and control of one or more components in the

system **100**. Each of the operator stations **132** could, for example, represent a computing device running a MICROSOFT WINDOWS operating system.

At least one router/firewall **134** couples the networks **128** to one or more networks **136**. The router/firewall **134** includes any suitable structure for providing communication between networks, such as a secure router or combination router/firewall. The network **136** could represent any suitable network, such as an enterprise-wide Ethernet or other network or all or a portion of a larger network (such as the Internet).

In the Purdue model, "Level 5" may include one or more enterprise-level controllers **138** coupled to the network **136**. Each enterprise-level controller **138** is typically able to perform planning operations for multiple plants **101a-101n** and to control various aspects of the plants **101a-101n**. The enterprise-level controllers **138** can also perform various functions to support the operation and control of components in the plants **101a-101n**. As particular examples, the enterprise-level controller **138** could execute one or more order processing applications, enterprise resource planning (ERP) applications, advanced planning and scheduling (APS) applications, or any other or additional enterprise control applications. Each of the enterprise-level controllers **138** includes any suitable structure for providing access to, control of, or operations related to the control of one or more plants. Each of the enterprise-level controllers **138** could, for example, represent a server computing device running a MICROSOFT WINDOWS operating system. In this document, the term "enterprise" refers to an organization having one or more plants or other processing facilities to be managed. Note that if a single plant **101a** is to be managed, the functionality of the enterprise-level controller **138** could be incorporated into the plant-level controller **130**.

Access to the enterprise-level controllers **138** may be provided by one or more operator stations **140**. Each of the operator stations **140** includes any suitable structure for supporting user access and control of one or more components in the system **100**. Each of the operator stations **140** could, for example, represent a computing device running a MICROSOFT WINDOWS operating system.

A historian **142** is also coupled to the network **136** in this example. The historian **142** could represent a component that stores various information about the system **100**. The historian **142** could, for example, store information used during production scheduling and optimization. The historian **142** represents any suitable structure for storing and facilitating retrieval of information. Although shown as a single centralized component coupled to the network **136**, the historian **142** could be located elsewhere in the system **100**, or multiple historians could be distributed in different locations in the system **100**.

At least one of the controllers shown in FIG. 1 could denote a model-based controller that operates using one or more process models **144**. For example, each of the controllers **106** could operate using one or more process models **144** to determine, based on measurements from one or more sensors **102a**, how to adjust one or more actuators **102b**. In some embodiments, each model **144** associates one or more manipulated or disturbance variables with one or more controlled variables. A controlled variable (CV) generally represents a variable that can be measured or inferred and that is ideally controlled to be at or near a desired setpoint or within a desired range of values. A manipulated variable (MV) generally represents a variable that can be adjusted in order to alter one or more controlled variables. A disturbance variable (DV) generally denotes a variable whose value can

be considered but cannot be controlled. As a simple example, a flow rate of material through a pipe could denote a controlled variable, a valve opening for a valve that controls the flow rate of material could denote a manipulated variable, and an ambient temperature around the pipe or the valve could denote a disturbance variable.

As noted above, the process models **144** need to be reasonably accurate for model-based controllers to operate effectively, and the process models **144** typically need to be updated as conditions related to an industrial process change. However, it is often difficult to determine from routine operating data whether a model accurately describes the true process behavior of an industrial process, and performing experiments to gather data in order to determine whether a model accurately describes the true process behavior of an industrial process is often undesirable.

In accordance with this disclosure, at least one component of the system **100** includes a tool **146** that analyzes routine operating data for a model-based controller in order to detect significant model-plant mismatch. Example processes for detecting significant model-plant mismatch are described below. Also, as described in more detail below, the tool **146** can use a support vector machine (SVM) as part of the analysis of the routine operating data. One example benefit of using these techniques is that significant model-plant mismatch can be automatically determined so that a model-based controller can have its model **144** updated or replaced before the model-plant mismatch causes losses due to poor process control.

The tool **146** could be implemented in any suitable manner and using any suitable device. For example, the tool **146** could reside on any of the controllers or operator stations shown in FIG. **1**. The tool **146** could also reside on any other suitable device(s) in FIG. **1**, such as on a dedicated computing device. The tool **146** could be implemented using any suitable hardware or any suitable combination of hardware and software/firmware instructions. In particular embodiments, the tool **146** is implemented using software/firmware instructions that are executed by at least one processor of a computing device.

Although FIG. **1** illustrates one example of an industrial process control and automation system **100**, various changes may be made to FIG. **1**. For example, a control system could include any number of sensors, actuators, controllers, servers, operator stations, networks, models, tools, and other components. Also, the makeup and arrangement of the system **100** in FIG. **1** is for illustration only. Components could be added, omitted, combined, further subdivided, or placed in any other suitable configuration according to particular needs. Further, particular functions have been described as being performed by particular components of the system **100**. This is for illustration only. In general, process control and automation systems are highly configurable and can be configured in any suitable manner according to particular needs. In addition, while FIG. **1** illustrates one example environment in which model-plant mismatch detection using model parameter data clustering can be used, this functionality can be used in any other suitable device or system.

FIG. **2** illustrates a second example industrial process control and automation system **200** according to this disclosure. In particular, the system **200** of FIG. **2** denotes an example web manufacturing or processing system. As shown in FIG. **2**, the system **200** includes a paper machine **202**, a controller **204**, and a network **206**. The paper machine **202** includes various components used to produce a paper product, namely a paper web **208** that is collected at a reel

210. The controller **204** monitors and controls the operation of the paper machine **202**, which may help to maintain or increase the quality of the paper web **208** produced by the paper machine **202**.

In this example, the paper machine **202** includes at least one headbox **212**, which distributes a pulp suspension uniformly across the machine onto a continuous moving wire screen or mesh **213**. The pulp suspension entering the headbox **212** may contain, for example, 0.2-3% wood fibers, fillers, and/or other materials, with the remainder of the suspension being water. Arrays of drainage elements **214**, such as vacuum boxes, remove as much water as possible to initiate the formation of the web **208**. An array of steam actuators **216** produces hot steam that penetrates the paper web **208** and releases the latent heat of the steam into the paper web **208**. An array of rewet shower actuators **218** adds small droplets of water (which may be air atomized) onto the surface of the paper web **208**. The paper web **208** is then often passed through a calender having several nips of counter-rotating rolls. Arrays of induction heating actuators **220** heat the shell surfaces of various ones of these rolls.

Two additional actuators **222-224** are shown in FIG. **2**. A thick stock flow actuator **222** controls the consistency of incoming stock received at the headbox **212**. A steam flow actuator **224** controls the amount of heat transferred to the paper web **208** from drying cylinders. The actuators **222-224** could, for example, represent valves controlling the flow of stock and steam, respectively. These actuators may be used for controlling the dry weight and moisture of the paper web **208**. Additional flow actuators may be used to control the proportions of different types of pulp and filler material in the thick stock and to control the amounts of various additives (such as retention aid or dyes) that are mixed into the stock.

This represents a brief description of one type of paper machine **202** that may be used to produce a paper product. Additional details regarding this type of paper machine **202** are well-known in the art and are not needed for an understanding of this disclosure. Also, while described as being used to manufacture a paper web, other types of machines for manufacturing or processing any suitable webs could be used.

In order to control the paper-making process, one or more properties of the paper web **208** may be continuously or repeatedly measured. The web properties can be measured at one or various stages in the manufacturing process. This information may then be used to adjust the paper machine **202**, such as by adjusting various actuators within the paper machine **202**. This may help to compensate for any variations of the web properties from desired targets, which may help to ensure the quality of the web **208**. As shown in FIG. **2**, the paper machine **202** includes one or more scanners **226-228**, each of which may include one or more sensors. Each scanner **226-228** is capable of measuring one or more characteristics of the paper web **208**. For example, each scanner **226-228** could include sensors for measuring the tension, caliper, moisture, anisotropy, basis weight, color, gloss, sheen, haze, surface features (such as roughness, topography, or orientation distributions of surface features), or any other or additional characteristics of the paper web **208**.

Each scanner **226-228** includes any suitable structure or structures for measuring or detecting one or more characteristics of the paper web **208**, such as one or more sets of sensors. The use of scanners represents one particular embodiment for measuring web properties. Other embodiments could be used, such as those including one or more

stationary sets or arrays of sensors, deployed in one or a few locations across the web or deployed in a plurality of locations across the whole width of the web such that substantially the entire web width is measured.

The controller **204** receives measurement data from the scanners **226-228** and uses the data to control the paper machine **202**. For example, the controller **204** may use the measurement data to adjust any of the actuators or other components of the paper machine **202**. The controller **204** includes any suitable structure for controlling the operation of at least part of the paper machine **202**, such as a computing device. Note that while a single controller **204** is shown here, multiple controllers **204** could be used, such as different controllers that control different variables of the web.

The network **206** is coupled to the controller **204** and various components of the paper machine **202** (such as the actuators and scanners). The network **206** facilitates communication between components of the system **200**. The network **206** represents any suitable network or combination of networks facilitating communication between components in the system **200**. The network **206** could, for example, represent a wired or wireless Ethernet network, an electrical signal network (such as a HART or FOUNDATION FIELDBUS network), a pneumatic control signal network, or any other or additional network(s).

The controller(s) **204** can operate to control one or more aspects of the paper machine **202** using one or more models **230**. For example, each model **230** could associate one or more manipulated or disturbance variables with one or more controlled variables. The controlled variables typically include one or more properties of the web **208**. The manipulated variables typically include setpoints, settings, or other values used by various actuators in the system **200**.

In accordance with this disclosure, at least one component of the system **200** includes a tool **232** that analyzes routine operating data for a model-based controller in order to detect significant model-plant mismatch. The process for detecting significant model-plant mismatch is described below. Also, as described in more detail below, the tool **232** can use a support vector machine as part of the analysis of the routine operating data. The tool **232** could be implemented in any suitable manner and using any suitable device, such as when the tool **232** resides on the controller **204** or a dedicated computing device. The tool **232** could be implemented using any suitable hardware or any suitable combination of hardware and software/firmware instructions, such as when the tool **232** is implemented using software/firmware instructions that are executed by at least one processor of a computing device.

Although FIG. 2 illustrates another example of an industrial process control and automation system **200**, various changes may be made to FIG. 2. For example, other systems could be used to produce other paper or non-paper products.

Also, while shown as including a single paper machine **202** with various components and a single controller **204**, the system **200** could include any number of paper machines or other machinery having any suitable structure, and the system **200** could include any number of controllers. In addition, while FIG. 2 illustrates another example environment in which model-plant mismatch detection using model parameter data clustering can be used, this functionality can be used in any other suitable device or system.

FIG. 3 illustrates an example device **300** supporting model-plant mismatch detection using model parameter data clustering according to this disclosure. The device **300** could, for example, represent any of the devices in FIGS. 1

and 2 that can execute the tool **146, 232**. However, the device **300** could be used in any other suitable system, and the tool **146, 232** could be implemented using any other suitable device.

As shown in FIG. 3, the device **300** includes at least one processing device **302**, at least one storage device **304**, at least one communications unit **306**, and at least one input/output (I/O) unit **308**. The processing device **302** executes instructions that may be loaded into a memory device **310**. The processing device **302** may include any suitable number(s) and type(s) of processors or other devices in any suitable arrangement. Example types of processing devices **302** include microprocessors, microcontrollers, digital signal processors, field programmable gate arrays, application specific integrated circuits, and discrete logic devices.

The memory device **310** and a persistent storage **312** are examples of storage devices **304**, which represent any structure(s) capable of storing and facilitating retrieval of information (such as data, program code, and/or other suitable information on a temporary or permanent basis). The memory device **310** may represent a random access memory or any other suitable volatile or non-volatile storage device(s). The persistent storage **312** may contain one or more components or devices supporting longer-term storage of data, such as a read only memory, hard drive, Flash memory, or optical disc.

The communications unit **306** supports communications with other systems or devices. For example, the communications unit **306** could include a network interface card or a wireless transceiver facilitating communications over a wired or wireless network. The communications unit **306** may support communications through any suitable physical or wireless communication link(s).

The I/O unit **308** allows for input and output of data. For example, the I/O unit **308** may provide a connection for user input through a keyboard, mouse, keypad, touchscreen, or other suitable input device. The I/O unit **308** may also send output to a display, printer, or other suitable output device.

Although FIG. 3 illustrates one example of a device **300** supporting model-plant mismatch detection using model parameter data clustering, various changes may be made to FIG. 3. For example, various components in FIG. 3 could be combined, further subdivided, rearranged, or omitted and additional components could be added according to particular needs. Also, computing devices can come in a wide variety of configurations, and FIG. 3 does not limit this disclosure to any particular configuration of computing device.

FIG. 4 illustrates an example method **400** for model-plant mismatch detection using model parameter data clustering according to this disclosure. For ease of explanation, the method **400** is described below as being implemented using the device **300** of FIG. 3 in the systems **100, 200** of FIGS. 1 and 2. However, the method **400** could be performed using any suitable device and in any suitable system.

As shown in FIG. 4, routine operating data associated with a model-based industrial process controller is obtained at step **402**. This could include, for example, the processing device **302** that executes the tool **146, 232** obtaining data associated with operation of a model-based controller (such as a controller **106** or **204**) from that controller or from another device. If the tool **146, 232** is executed within the controller **106** or **204**, this could include the processing device **302** collecting the routine operating data during execution of control logic by the controller.

Model parameters for a process model representing an underlying industrial process are repeatedly estimated dur-

ing multiple periods of time at step 404. This could include, for example, the processing device 302 that executes the tool 146, 232 performing a model identification algorithm using the routine operating data to identify parameters for a process model. There are a number of model identification algorithms and tools that are known in the art. This could be repeated at a specified interval or at other times. In some embodiments, the tool 146, 232 uses a moving or sliding window of data and uses the data within the window to estimate the model parameters each time the model identification algorithm is executed.

One or more clusters of the model parameter sets are identified at step 406. Since the quality of the routine operating data used in step 404 may be low, the estimates of the model parameters can have a lot of uncertainty around them. However, the sets of parameter estimates can form a cluster over time. This step could include, for example, the processing device 302 that executes the tool 146, 232 using a support vector machine to determine the clustering of the model parameter sets. A support vector machine could implement a kernel function that generates a linear or nonlinear clustering of data by mapping original data into a space where a cluster boundary can be identified.

Additional model parameter sets for the process model are estimated during one or more additional periods of time at step 408. This could include, for example, the processing device 302 that executes the tool 146, 232 performing the same operations as in step 404 with different data to identify the additional model parameter sets. A determination is made whether any of the additional model parameter sets falls outside of the identified cluster(s) at step 410. This could include, for example, the processing device 302 that executes the tool 146, 232 determining whether any of the additional model parameter sets is separated from an identified cluster by at least some threshold distance. If so, this is indicative of a significant change to the underlying industrial process, and some type of corrective action can be taken at step 412. This could include, for example, the processing device 302 that executes the tool 146, 232 generating an alarm indicating that a model-plant mismatch has been detected. Operators may then perform or initiate a model identification process to collect data in order to generate a new process model or to update an existing process model. This may also include the processing device 302 initiating a model identification process to collect data in order to generate a new process model or to update an existing process model. The model identification process could be performed by the processing device 302 or by another device. Any other or additional actions could also occur in response to an identified model-plant mismatch.

Although FIG. 4 illustrates one example of a method 400 for model-plant mismatch detection using a support vector machine to cluster data, various changes may be made to FIG. 4. For example, while shown as a series of steps, various steps in FIG. 4 could overlap, occur in parallel, occur in a different order, or occur any number of times.

Additional details regarding specific techniques for model-plant mismatch detection using model parameter data clustering are provided below. Note that the details provided below are examples only and that other implementations of the techniques described in this patent document could be used. Also note that while specific details are provided below, other implementations of the techniques described below could be used.

The following describes a framework for model-plant mismatch (MPM) detection based on a novel closed-loop identification approach and a one-class support vector

machine (SVM) learning technique. With this scheme, the detection framework can monitor for both model-plant mismatch and noise model changes separately, thus discriminating the model-plant mismatch from the noise model changes. This approach is applicable to routine operating data that may lack external excitations. It can be shown that the closed-loop identification techniques described below furnish a consistent and Gaussian distributed parameter estimate for a process model. An SVM model can be built based on process and noise model estimates from training data to predict the occurrence of model-plant mismatch.

In general, the approach described below involves the following. Routine operating data is partitioned into "training" data (believed to contain no model-plant mismatch) and "testing" data. The training data serves as a benchmark, and the presence of model-plant mismatch in the testing data is detected using that benchmark. Based on closed-loop identification and support vector machine classification, model-plant mismatch and noise changes can be detected independently, allowing this approach to discriminate model-plant mismatch from noise model changes. This can occur with or without external excitations. FIGS. 5 through 7 illustrate example uses of model-plant mismatch detection according to this disclosure.

Model-Plant Mismatch Detection Algorithm

This section explains the overall concept of detecting the presence of model-plant mismatch with routine operating data. Note that noise model change detection can follow the same general process as model-plant mismatch detection. Thus, in the following description, model-plant mismatch detection is described in detail, but the same or similar approach could be used for noise model change detection.

The model-plant mismatch detection algorithm is based generally on a novel closed-loop identification technique, which is capable of supplying consistent estimates for a process model with routine operating data (assuming the data is sufficiently exciting for relevant system identification objectives). However, the inevitable variance associated with process model estimates could impede direct comparisons of results with nominal models to expose mismatches. In other words, discrepancies between model estimates and true models cannot always be blamed on model-plant mismatch and might be attributed merely to variance. Because of this, a reasonable variation range (or an uncertainty bound) around an estimated process model due to the variance of parameter estimates can be determined, and elements outside this range can be regarded as mismatched models. Such a range can be naturally portrayed using the SVM technique. Note that to synthesize all possible mismatch situations (such as gain mismatches and time constant mismatches) with an overall metric, process model estimates can be estimated using finite impulse response (FIR) forms. Measuring differences in high-dimensional spaces can be non-trivial, which leads to the use of a support vector machine for this task.

FIG. 5 illustrates the concept of detecting model-plant mismatch, where routine operating data is split or divided into training data and testing data. In FIG. 5, there are two training stages 502a-502b (which include routine operating data classified as training data) and two test stages 504a-504b (which include routine operating data classified as testing data). The training data is collected during one or more time intervals in which model-plant mismatch is not likely present, such as periods during or right after a model identification stage.

A moving window can be used to process the routine operating data, and the size of the training data can be

selected according to the window size. For each window, closed-loop identification can be applied to attain an estimate of the process model. A one-class SVM can be trained using the estimated process models determined with the training data, and the SVM can be viewed as an appropriate bound encompassing the estimated process models.

FIG. 6 illustrates the concept of detecting model-plant mismatch with an SVM technique. In FIG. 6, each point 602 stands for an FIR representation of a model. The models in circles are those obtained from training data, and they form a benchmarking cluster 604. The models in cross points are those obtained from testing data, and those models outside the benchmarking cluster 604 are viewed as mismatched models. Any model inside the boundary of the benchmarking cluster 604 is considered normal, indicating the absence of model-plant mismatch.

For the testing data, a moving window is again used, and closed-loop identification can be applied to attain an estimate of the process model for each window. Each process model estimate obtained during testing is examined by the support vector machine to predict whether it is located inside the boundary of the benchmarking cluster 604. If so, the support vector machine returns a value (such as a positive score) indicating that no model-plant mismatch has been detected. Otherwise, the support vector machine returns a different value (such as a negative score) to indicate the presence of model-plant mismatch in the current window. To be cautious in triggering an identification experiment, an MPM alarm might not be raised until a specified number of MPM indications have been obtained, such as a specified number of negative scores within a specified time period. Note that all of the training and testing operations can be performed with routine operating data free of external excitations.

Closed-Loop Identification

As can be seen from the above description, closed-loop identification is used repeatedly in the proposed MPM detection algorithm, namely to (i) identify process models with training data in order to train the SVM and (ii) identify process models with testing data to detect model-plant mismatch. Various closed-loop identification techniques have been developed over the years, such as direct identification, indirect identification, joint input-output identification, and projection. However, none of these approaches may be suitable for use in the MPM detection problem. For example, the latter three identification techniques require the inclusion of an external dither signal and/or a linear feedback controller, while the direct identification method often leads to biased estimates of a process model if the noise model structure is not sufficiently specified. Described below is a novel closed-loop identification approach that aims to resolve the bias issue and fit into the MPM detection context. It can be shown that the proposed technique gives consistent estimates for a process model provided some mild technical assumptions are satisfied.

Consider the following single-input single-output (SISO) Box-Jenkins plant:

$$y(t) = G_0(q)u(t) + H_0e(t) \tag{1}$$

where G_0 and H_0 denote the true plant model and the true noise model, respectively. Suppose that H_0 is monic, stable, and inversely stable. The plant $G_0(q)$ is assumed to contain at least one sample delay, q is the unit-shift operator, and $e(t)$ is assumed to be zero-mean Gaussian white noise with constant variance σ^2 . Here, $y(t)$ and $u(t)$ represent the output and input signals, respectively, and it is assumed that all relevant signals are quasi-stationary. In a closed loop with

MPC, a feedback controller often displays nonlinear dynamics (if the constraints are active). This can be expressed as:

$$u(t) = k(t, u^{t-1}, y^t) \tag{2}$$

where $u^{t-1} = [u(1), \dots, u(t-1)]$ and $y^t = [y(1), \dots, y(t)]$.

For cases with external excitations, a persistently-exciting dither signal can guarantee that closed-loop data is informative, regardless of the controller order. Without external excitations, to achieve the informativity requirement for linear controllers, the following relationship can be satisfied for Box-Jenkins models:

$$\max(n_x - n_p, n_y - n_d) \geq n_d + \min(n_x, n_p) \tag{3}$$

where n_x and n_y denote the numerator and denominator orders of the linear controller, respectively. Also, n_b and n_f denote the orders of the process model numerator and denominator polynomials, respectively. Further, n_d denotes the order of the numerator polynomial of the noise model. One observation from Equation (3) is that complex controllers and a larger time-delay often imply richer information in closed-loop data. Additionally, if the controller is nonlinear (as is often the case of an MPC), closed-loop data is generally sufficiently exciting for relevant system identification. Another benefit of using a nonlinear controller is that it can prevent the identification algorithm from identifying the controller inverse as the process model estimate. Moreover, a priori information about the time delay can be available and specified to the identification algorithm.

The bias associated with direct closed-loop identification arises from improper specification of the noise model structure. In order to circumvent this limitation, an FIR model can be used as the noise model structure. Specifically, the true process model of Equation (1) can be re-written into an equivalent form as follows:

$$\frac{1}{H_0} y(t) = \frac{1}{H_0} G_0(q)u(t) + e(t) \tag{4}$$

This can be represented using an infinite-order autoregressive exogenous (AR) model with:

$$A_0(q)y(t) = B_0(q)u(t) + e(t) \tag{5}$$

Here:

$$A_0(q) = \frac{1}{H_0(q)} = 1 + a_1^0 q^{-1} + \dots + a_n^0 q^{-n} + \dots \tag{6}$$

$$B_0(q) = A_0(q)G_0(q) = b_0^0 q^{-d} + b_1^0 q^{-d-1} + \dots + b_n^0 q^{-d-n} + \dots \tag{7}$$

where d is the true time-delay. The proposed closed-loop identification described below includes two general steps: (i) high-order ARX model estimation from closed-loop data and (ii) output-error (OE) identification with filtered input-output data (where the filter is chosen as the estimated $A_0(q)$ polynomial).

High-Order ARX Model Identification

For an open-loop stable system, it can be shown that the coefficients of $A_0(q)$ are vanishing for growing n , and the same holds for $B_0(q)$. Thus, the infinite-order ARX model of Equation (5) can be parameterized using a high-order ARX model as follows:

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$$A(q, \eta_n)y(t) = B(q, \eta_n)u(t) + e(t) \quad (8)$$

where:

$$A(q, \eta_n) = 1 + \sum_{k=1}^n a_k q^{-k}, B(q, \eta_n) = \sum_{k=0}^n b_k q^{-d-k} \quad (9)$$

Denote:

$$\eta_n = [a_1 \dots a_n \ b_1 \dots b_n]^T \quad (10)$$

$$\eta_0 = [a_1^0 \dots a_n^0 \ b_1^0 \dots b_n^0 \dots]^T \quad (11)$$

For notational simplicity, choose $A(q, \eta_n)$ and $B(q, \eta_n)$ to be of the same order. To reduce large parameter covariance resulting from high orders, a regularization term can be added here.

Suppose that the following relationship holds for the selected high-order ARX model structure shown in Equation (8):

$$n \rightarrow \infty, n^{3+\delta}/N \rightarrow 0, \text{ as } N \rightarrow \infty \quad (12)$$

where n is the order of Equation (8), N is the sample number, and $\delta > 0$ is a constant. With this assumption, the following can be obtained:

$$\sup_{\omega} |A(e^{j\omega}, \hat{\eta}_n) - A_0(e^{j\omega})| \rightarrow 0, \text{ w.p.1, as } N \rightarrow \infty \quad (13)$$

where:

$$\hat{\eta}_n = [\hat{a}_1 \dots \hat{a}_n \ \hat{b}_1 \dots \hat{b}_n]^T \quad (14)$$

represents the estimate of parameter vector η_n .

It can be shown that when the order of the high-order ARX model in Equation (8) increases to infinity (but with a much slower increase rate than N), the estimate $A(e^{j\omega}, \hat{\eta}_n)$ converges uniformly to the true polynomial $A_0(e^{j\omega})$ with a probability of one. This essentially depicts the behavior of the high-order ARX model under a large number of data samples. This provides a theoretical basis for the subsequent OE identification with filtered input and output data since the estimated filter $A(e^{j\omega}, \hat{\eta}_n)$ approximates the true filter $A_0(e^{j\omega})$ sufficiently well. Note that $n \rightarrow \infty$ is merely an assumption for theoretical derivations, and a finite n that is based on apriori information regarding the noise model could be used when implementing the identification algorithm.

OE Identification with Filtered Input-Output Data

Replacing $H_0(q)$ in Equation (4) with the inverse of the estimated noise model $A(e^{j\omega}, \hat{\eta}_n)$ from Equation (13), the following can be obtained:

$$y(t, \hat{\eta}_n) = G_0(q)u(t, \hat{\eta}_n) + e(t) \quad (15)$$

where $y(t, \hat{\eta}_n)$ represents the signal filtered through $A(q, \eta)$. A similar definition can be provided for $u(t, \hat{\eta}_n)$. To identify $G_0(q)$, an FIR model to $G_0(q)$ can be specified if no a priori information is available. However, in typical industrial processes, some knowledge is available to correctly parameterize the plant model. For example, in the machine direction (MD) process of paper machines, it is widely accepted that a first-order plus time-delay model is sufficient to precisely capture the system dynamics.

With this in mind, an OE identification could occur as follows:

$$y(t, \hat{\eta}_n) = G(q, \rho)u(t, \hat{\eta}_n) + e(t) \quad (16)$$

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where $G(q, \rho)$ is a correctly-selected plant model structure. The parameter ρ could be estimated by minimizing the following criterion:

$$\hat{\rho}_N = \arg \min_{\rho \in \Omega_\rho} \frac{1}{N} \sum_{t=1}^N \frac{1}{2} \varepsilon^2(t, \rho, \hat{\eta}_N) \quad (17)$$

where Ω_ρ is a compact set. The prediction error $\varepsilon(t, \rho, \hat{\eta}_n)$ can be defined as:

$$\varepsilon(t, \rho, \hat{\eta}_n) = [G_0(q) - G(q, \rho)]u(t, \hat{\eta}_n) + \frac{A(q, \hat{\eta}_n)}{A_0(q)} e(t) \quad (18)$$

With respect to the parameter estimate $\hat{\rho}_N$, consider the true Box-Jenkins model for the plant as specified in Equation (1), as well as the equivalent high-order ARX form in Equation (5). Assuming the plant model is correctly parameterized and the parameter estimates $\hat{\rho}_N$ from the prediction error criterion in Equation (17) are consistent, the following can be obtained:

$$\hat{\rho}_N \rightarrow \rho_0, \text{ w.p.1, as } N \rightarrow \infty \quad (19)$$

where ρ_0 is the true parameter value of G_0 . Moreover, the parameter estimates $\hat{\rho}_N$ are Gaussian distributed with mean value ρ_0 .

Despite the premise on the correct parameterization of $G_0(q)$ above, this is not a restrictive limitation on the proposed closed-loop identification method. As described below, the support vector machine in the MPM detection is trained and tested on the FIR form of $G(q, \hat{\rho}_N)$. Thus, if a priori information on $G_0(q)$ is not accessible, a FIR model could be used in the OE identification to eliminate bias.

Compared with existing closed-loop identification methods, the proposed approach can have various advantages. For example, the proposed approach may require no information about a controller and thus is applicable to closed-loop data with both linear and nonlinear controllers. Also, the proposed approach does not rely on external excitations but is suitable for cases with external excitations. In addition, a consistent estimate of a process model can be obtained even if a priori information about the noise model is not available. Note that the explicit expression of the variance of $\hat{\rho}_N$ is nontrivial, so it may be recommended to use a set of training data from which a group of process model estimates can be obtained and used as an approximation of the variance of transfer function estimates. From this standpoint, more training data could be preferred.

One-Class Learning SVM

As a convention, a support vector machine can be useful particularly for binary classification problems in machine learning. A support vector machine searches for a hyperplane that separates two classes of data with a maximum distance to either class. One example benefit of such a hyperplane is its robustness to outliers, which can help to considerably reduce false classifications. For MPM detection, the process models generated using the training data can be used as a reference group representing the behavior of a "no mismatch" process model cluster. However, the other group of data is ordinarily not accessible since abnormal situations may occur in a variety of ways (such as various parametric mismatches, irregular disturbances, and so on). Thus, MPM detection is a one-class learning problem, which is also known as a "novelty detection problem."

A one-class learning SVM is depicted in a feature space, meaning a space to which data is mapped. Consider the following set of training data samples:

$$x_1, x_2, \dots, x_l \in X \subset R^m \quad (20)$$

where l is the number of training data values and X is a subset (called an input space) of R^m . Before training the one-class SVM, data is mapped through $\Phi: X \rightarrow F$ into a higher-dimensional feature space F . A kernel function $K(x, y)$ could be used such that the inner product in the feature space can be evaluated in the input space as:

$$K(x, y) = \langle \Phi(x), \Phi(y) \rangle, \forall x, y \in X \quad (21)$$

A well-known kernel function that could be used is the Gaussian kernel:

$$K(x, y) = e^{-\|x-y\|^2/c} \quad (22)$$

With a Gaussian kernel function, data points in the feature space are located in the same quadrant since $K(x, y) > 0, \forall x, y \in X$. Thus, it is possible to find a hyperplane to separate the origin from the training data in the feature space with maximized margin.

With this idea, the one-class SVM training problem could be formulated as follows:

$$\min_{w, \xi, b} \frac{1}{2} \|w\|^2 + \frac{1}{v} \sum_{i=1}^l \xi_i - b \quad (23)$$

$$\text{s.t. } w^T \Phi(x_i) \geq b - \xi_i, \xi_i \geq 0 \quad (24)$$

where w and b represent the slope and offset of the hyperplane in the feature space. The term $v \in [0, 1]$ is a parameter tuning the upper bound of the fraction of outliers and the lower bound of the fraction of support vectors. The term is a slack variable allowing for local violations of the hard boundary determined by the hyperplane.

The above optimization problem can be solved, such as by quadratic programming, giving rise to a sparse solution. Here, sparse means that the solution to Equation (23) can be completely determined using a small number of support vectors. With the optimizing variables \hat{w} and \hat{b} , the decision (or score value) function can be described as:

$$h(x) = \hat{w}^T \Phi(x) - \hat{b} \quad (25)$$

The solution \hat{w} is a convex combination of images of support vectors in the feature space through the mapping Φ . As a result, the inner product in the predictor function in Equation (25) can be calculated via the kernel function rather than in the high-dimensional feature space. The introduction of kernel functions significantly expands the flexibility in constructing separating hyperplanes, enabling the SVM to generate a nonlinear boundary.

One issue in applying a one-class SVM training strategy is the limited amount of training data provided by the industry. Taking a paper machine as an example, grade changes (setpoint changes) often take place on a daily basis, and training data has to be collected after each grade change to represent the current operating condition of the paper machine before carrying out MPM detection. Consequently, only a few process model estimates from training data may be available to build an SVM model. In order to overcome this issue, a resampling technique could be used to enlarge the cluster of "no mismatch" models estimated from training data before performing SVM training.

To perform the resampling technique, a probability density function (PDF) can be fit to each impulse response (IR)

coefficient of an estimated process model. Then, a large number of samples can be generated by sampling randomly from the fitted probability density function. For example, denote the FIR form of the estimated process model $G(q, \hat{\rho}_N)$ in the k^{th} moving window as:

$$G(q, \hat{\rho}_N^k) = \hat{g}_0^k q^d + \hat{g}_1^k q^{d+1} + \dots + \hat{g}_m^k q^{d+m} \quad (26)$$

Here, m is a pre-specified number, and $k=1, 2, \dots, N_k$ are indices for the moving window in the training data. The FIR coefficients \hat{g}_i^k (for $i=0, \dots, m$) are Gaussian distributed since $\hat{\rho}_N$ has a Gaussian distribution. For each coefficient \hat{g}_i^k , several estimated values are attained from the moving window in the training data. Then, rough estimators for the mean and variance of each IR coefficient can be constructed as follows:

$$\hat{\mu}_i = \mu(\hat{g}_i^1, \hat{g}_i^2, \dots, \hat{g}_i^{N_k}), i=0, \dots, m \quad (27)$$

$$\hat{\sigma}_i^2 = \sigma(\hat{g}_i^1, \hat{g}_i^2, \dots, \hat{g}_i^{N_k}), i=0, \dots, m \quad (28)$$

where $\mu(\cdot)$ and $\sigma(\cdot)$ are functions, such as the sample mean and sample variance.

Due to the limited amount of training data (N_k normally is small), the estimated PDF for each FIR coefficient can be much more conservative compared with the true probability density function. Thus, a parameter α can be used to tune the width of the probability density function to avoid this problem. One potential rule of thumb in selecting α is to use a small value if there is a large amount of training data or a large value if there is a small amount of training data. A larger scaling factor may make the mismatch detection algorithm less sensitive to mismatch, while a smaller scaling factor may make the mismatch detection algorithm more sensitive to mismatch.

Once the rough estimators are determined, a large number of samples of each FIR coefficient can be randomly generated, subject to the corresponding estimated probability density function. Then, a one-class SVM model can be developed from these enhanced samples for the initial cluster of "good" process models.

MPM Detection with SVM

Once the one-class SVM is trained, the trained SVM can be used to process additional model estimates to identify whether the additional model estimates are part of the cluster of "good" process models. The FIR coefficients of the process model identified from each moving window in the testing data can be estimated, such as by using the same procedure described above. Once the estimated FIR coefficients are obtained, the SVM model is applied to predict whether the estimated FIR coefficients belong to the initial cluster. If so, the SVM can return a positive score value or other value indicating that the current testing window does not display mismatch. Otherwise, the SVM can return a negative score or other value to signify a mismatch. However, to be cautious before starting a new identification experiment, a specified number of mismatch reports within some time period may need to be collected before triggering an alarm. For example, define I_t as the sign of the score value for time instant t :

$$I_t = \text{sign}(h(x_t)) \quad (29)$$

with x_t denoting the FIR coefficient vector of the plant model estimate for the window data at time t . Denote $T_t = \{t-n_T, t-1, t\}$, where n_T is a detection interval (the number of previous moving windows under inspection to determine the existence of MPM). Further define an MPM indicator as follows:

$$s = \frac{|L_-|}{|L_-| + |L_+|} \quad (30)$$

where $L_- := \{I_i = -1 : i \in T_i\}$, $L_+ := \{I_i \neq -1 : i \in T_i\}$, and $|S|$ is the number of elements in the set S . A user could specify a threshold s_T for the MPM indicator to raise an MPM alarm (such as a conservative s_T value like 0.95) to be circumspect in reporting the MPM alarm.

Note that the MPM detection method presented above can also be applied to the noise model estimate $A(q, \hat{\eta}_n)$ from Equation (8) to find any noise model mismatch. In this way, the process and noise models can be monitored separately to distinguish model-plant mismatch from noise model changes.

Example results that could be obtained using these techniques are shown in FIG. 7, which relates to dry weight measurements associated with a web of paper being manufactured. In FIG. 7, time is divided into three periods **702-706**. Period **702** denotes a period of normal operation, period **704** denotes a period where model-plant mismatch actually exists, and period **706** denotes a period where both model-plant mismatch and noise model mismatch actually exist.

Line **708** in FIG. 7 denotes the scores generated by the mismatch detection algorithm for the plant model, and line **710** in FIG. 7 denotes a mismatch indicator that identifies whether model-plant mismatch is being detected. As can be seen in FIG. 7, the line **708** starts with values that are greater than zero and then transitions to values that are less than zero. The negative values are indicative of model-plant mismatch, so the line **710** transitions from values at or near zero to more positive values. Eventually, the line **710** could hit a maximum value, which is indicative of a specified number of SVM scores indicating model-plant mismatch.

Similarly, line **712** in FIG. 7 denotes the scores generated by the mismatch detection algorithm for a noise model, and line **714** in FIG. 7 denotes a mismatch indicator that identifies whether noise model mismatch is being detected. As can be seen in FIG. 7, the line **712** starts with values that are greater than zero and then transitions to values that are less than zero. The negative values are indicative of noise model mismatch, so the line **714** transitions from values at or near zero to more positive values. Eventually, the line **714** could hit a maximum value, which is indicative of a specified number of SVM scores indicating noise model mismatch.

The identification of a mismatch in the noise model without a corresponding mismatch in the plant model allows the mismatch detection algorithm to avoid a false alarm. Of course, in other instances, a mismatch in the noise model could raise an alert.

Although FIGS. 5 through 7 illustrate example uses of model-plant mismatch detection, various changes may be made to FIGS. 5 through 7. For example, these figures are provided merely to illustrate example functions or results associated with the model-plant mismatch detection algorithm. Other uses or implementations of the model-plant mismatch detection algorithm are possible, and FIGS. 5 through 7 do not limit this disclosure to any particular use or implementation.

Summary

This disclosure has presented a novel model-plant mismatch detection algorithm that can separate model-plant mismatch from noise model changes, and this technique is applicable to routine operating data that lacks external excitations. A novel closed-loop identification method has

been described that can give consistent parameter estimates for a process model without the need for any a priori information on the noise model. The mismatch detection problem is divided into a training stage and a testing stage.

5 In the training stage, an SVM model is developed based on process and noise model estimates. The SVM model is then used to predict the occurrence of model-plant mismatch in the testing data. This approach is tailored to satisfy industrial demands for model-plant mismatch monitoring.

10 Note that while often described as being used for model-plant mismatch detection with respect to an industrial process controller, the techniques described in this patent document can be applied to various situations where there is a mathematical model of a process and a desire to check (possibly continuously) if the true process behavior is changing from what was originally modelled. The parameters of a model can be monitored, and the model parameters are not necessarily associated with an industrial process controller.

20 In some embodiments, various functions described in this patent document are implemented or supported by a computer program that is formed from computer readable program code and that is embodied in a computer readable medium. The phrase "computer readable program code" includes any type of computer code, including source code, object code, and executable code. The phrase "computer readable medium" includes any type of medium capable of being accessed by a computer, such as read only memory (ROM), random access memory (RAM), a hard disk drive, a compact disc (CD), a digital video disc (DVD), or any other type of memory. A "non-transitory" computer readable medium excludes wired, wireless, optical, or other communication links that transport transitory electrical or other signals. A non-transitory computer readable medium includes media where data can be permanently stored and media where data can be stored and later overwritten, such as a rewritable optical disc or an erasable storage device.

25 It may be advantageous to set forth definitions of certain words and phrases used throughout this patent document. The terms "application" and "program" refer to one or more computer programs, software components, sets of instructions, procedures, functions, objects, classes, instances, related data, or a portion thereof adapted for implementation in a suitable computer code (including source code, object code, or executable code). The term "communicate," as well as derivatives thereof, encompasses both direct and indirect communication. The terms "include" and "comprise," as well as derivatives thereof, mean inclusion without limitation. The term "or" is inclusive, meaning and/or. The phrase "associated with," as well as derivatives thereof, may mean to include, be included within, interconnect with, contain, be contained within, connect to or with, couple to or with, be communicable with, cooperate with, interleave, juxtapose, be proximate to, be bound to or with, have, have a property of, have a relationship to or with, or the like. The phrase "at least one of," when used with a list of items, means that different combinations of one or more of the listed items may be used, and only one item in the list may be needed. For example, "at least one of: A, B, and C" includes any of the following combinations: A, B, C, A and B, A and C, B and C, and A and B and C.

30 The description in the present application should not be read as implying that any particular element, step, or function is an essential or critical element that must be included in the claim scope. The scope of patented subject matter is defined only by the allowed claims. Moreover, none of the claims invokes 35 U.S.C. § 112(f) with respect to any of the

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appended claims or claim elements unless the exact words “means for” or “step for” are explicitly used in the particular claim, followed by a participle phrase identifying a function. Use of terms such as (but not limited to) “mechanism,” “module,” “device,” “unit,” “component,” “element,” “member,” “apparatus,” “machine,” “system,” “processor,” or “controller” within a claim is understood and intended to refer to structures known to those skilled in the relevant art, as further modified or enhanced by the features of the claims themselves, and is not intended to invoke 35 U.S.C. § 112(f).

While this disclosure has described certain embodiments and generally associated methods, alterations and permutations of these embodiments and methods will be apparent to those skilled in the art. Accordingly, the above description of example embodiments does not define or constrain this disclosure. Other changes, substitutions, and alterations are also possible without departing from the spirit and scope of this disclosure, as defined by the following claims.

What is claimed is:

1. A method for controlling an operation of a paper machine in a web manufacturing system, the method comprising:

obtaining routine operating data associated with a model-based controller;

repeatedly identifying one or more values for one or more model parameters of at least one model associated with a process at multiple periods of time, the one or more values for the one or more model parameters identified using data associated with the process by estimating the one or more model parameters at each of the multiple periods of time;

clustering the values of the one or more model parameters into one or more clusters using a support vector machine, the support vector machine using a kernel function to generate a clustering of data by mapping the data into a space where a cluster boundary is identified;

identifying one or more additional values for the one or more model parameters using additional data which is different than the data associated with the process during one or more additional periods of time;

detecting using a tool, a mismatch between the at least one model and the process in response to determining that at least some of the one or more additional values fall outside of the one or more clusters, the tool analyzing the routine operating data for the model-based controller using the support vector machine for detecting the mismatch; and

taking corrective action in response to detecting the mismatch.

2. The method of claim 1, wherein:

the process comprises an industrial process; and
at least one industrial process controller is configured to control at least part of the industrial process using the at least one model.

3. The method of claim 2, wherein the corrective action comprises generating at least one new or updated model for the industrial process controller.

4. The method of claim 1, wherein repeatedly identifying the one or more values for the one or more model parameters comprises using a moving or sliding window of operating data associated with the process.

5. The method of claim 1, wherein identifying the one or more values and identifying the one or more additional values each comprises performing closed-loop model identification by:

identifying a first model using closed-loop data; and
filtering the closed-loop data based on the first model; and

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identifying a second model based on the filtered closed-loop data.

6. The method of claim 5, wherein:

the first model comprises a high-order autoregressive exogenous (ARX) model; and

the second model comprises an output-error (OE) model.

7. The method of claim 1, wherein the detected mismatch indicates that the process has changed and is no longer accurately represented by the at least one model.

8. An apparatus for controlling an operation of a paper machine in a web manufacturing system, the apparatus comprising:

at least one memory configured to store data associated with a process; and

at least one processing device configured to:

obtain routine operating data associated with a model-based controller;

repeatedly identify one or more values for one or more model parameters of at least one model associated with the process using the data associated with the process at multiple periods of time, the one or more values for the one or more model parameters identified using data associated with the process by estimating the one or more model parameters at each of the multiple periods of time;

cluster the values of the one or more model parameters into one or more clusters using a support vector machine, the support vector machine using a kernel function to generate a clustering of data by mapping the data into a space where a cluster boundary is identified;

identify one or more additional values for the one or more model parameters using additional data which is different than the data associated with the process during one or more additional periods of time; and
detect using a tool, a mismatch between the at least one model and the process in response to determining that at least some of the one or more additional values fall outside of the one or more clusters, the tool analyzing the routine operating data for the model-based controller using the support vector machine for detecting the mismatch; and

taking corrective action in response to detecting the mismatch.

9. The apparatus of claim 8, wherein:

the process comprises an industrial process; and
an industrial process controller is configured to control at least part of the industrial process using at least one model.

10. The apparatus of claim 9, wherein, to take the corrective action, the at least one processing device is configured to initiate generation of at least one new or updated model for the industrial process controller.

11. The apparatus of claim 8, wherein, to repeatedly identify the one or more values for the one or more model parameters, the at least one processing device is configured to use a moving or sliding window of operating data associated with the process.

12. The apparatus of claim 8, wherein, to identify the one or more values or the one or more additional values, the at least one processing device is configured to perform closed-loop model identification, the closed-loop model identification comprising:

identifying a first model using closed-loop data;

filtering the closed-loop data based on the first model; and

identifying a second model based on the filtered closed-loop data.

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13. The apparatus of claim 12, wherein:
 the first model comprises a high-order autoregressive
 exogenous (ARX) model; and
 the second model comprises an output-error (OE) model.

14. A non-transitory computer readable medium for con- 5
 trolling an operation of a paper machine in a web manufactur-
 ing system, containing instructions that, when executed
 by at least one processing device, cause the at least one
 processing device to:

obtain routine operating data associated with a model- 10
 based controller;

repeatedly identify one or more values for one or more
 model parameters of at least one model associated with
 a process at multiple periods of time, the one or more
 values for the one or more model parameters identified 15
 using data associated with the process by estimating the
 one or more model parameters at each of the multiple
 periods of time;

cluster the values of the one or more model parameters
 into one or more clusters using a support vector 20
 machine, the support vector machine using a kernel
 function to generate a clustering of data by mapping the
 data into a space where a cluster boundary is identified;

identify one or more additional values for the one or more
 model parameters using additional data which is dif- 25
 ferent than the data associated with the process during
 one or more additional periods of time; and

detect using a tool, a mismatch between the at least one
 model and the process in response to determining that
 at least some of the one or more additional values fall

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outside of the one or more clusters, the tool analyzing
 the routine operating data for the model-based control-
 ler using the support vector machine for detecting the
 mismatch; and

take corrective action in response to detecting the mis-
 match.

15. The non-transitory computer readable medium of
 claim 14, wherein:

the process comprises an industrial process;
 an industrial process controller is configured to control at
 least part of the industrial process using at least one
 model.

16. The non-transitory computer readable medium of
 claim 15, wherein the instructions that when executed cause
 the at least one processing device to take the corrective
 action comprise:

instructions that when executed cause the at least one
 processing device to initiate generation of at least one
 new or updated model for the industrial process con-
 troller.

17. The non-transitory computer readable medium of
 claim 14, wherein the instructions that when executed cause
 the at least one processing device to repeatedly identify the
 one or more values for the one or more model parameters
 comprise:

instructions that when executed cause the at least one
 processing device to use a moving or sliding window of
 operating data associated with the process.

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